Atmospheric Science Program (ASP)

CHIEF SCIENTIST REPORT

Aerosol Forcing, Climate Sensitivity and Energy

DOE Climate Change Research Program Strategic Plan

Climate Change Science Program Synthesis and Assessment Product 2.3: Aerosols

Stephen E. Schwartz - ASP Chief Scientist

DOE Atmospheric Science Program Science Team Meeting

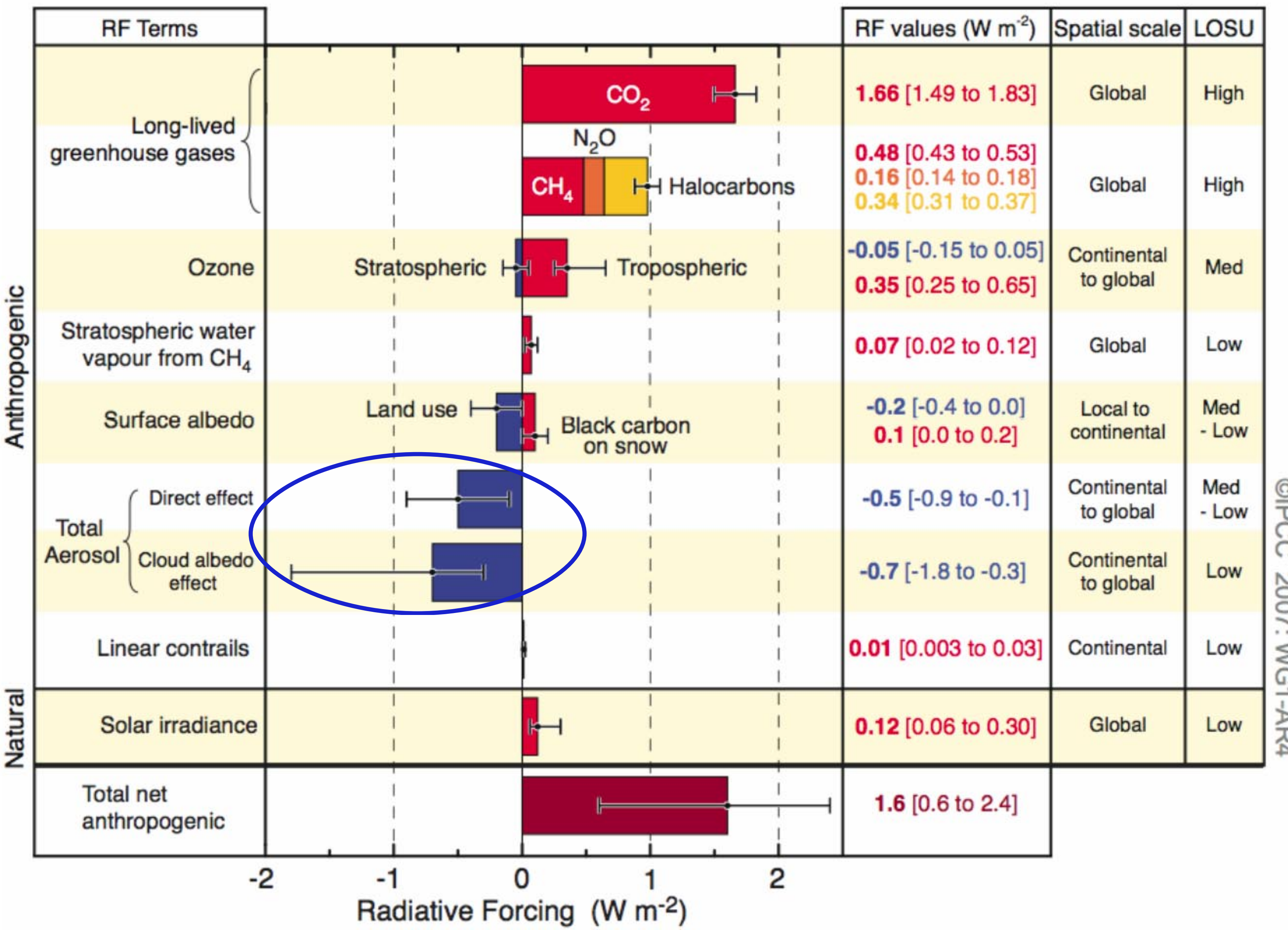
February 25-27, 2009

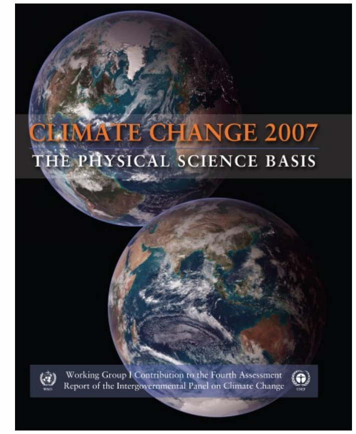
Santa Fe, New Mexico

AEROSOL FORCING, CLIMATE SENSITIVITY, AND ENERGY

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)





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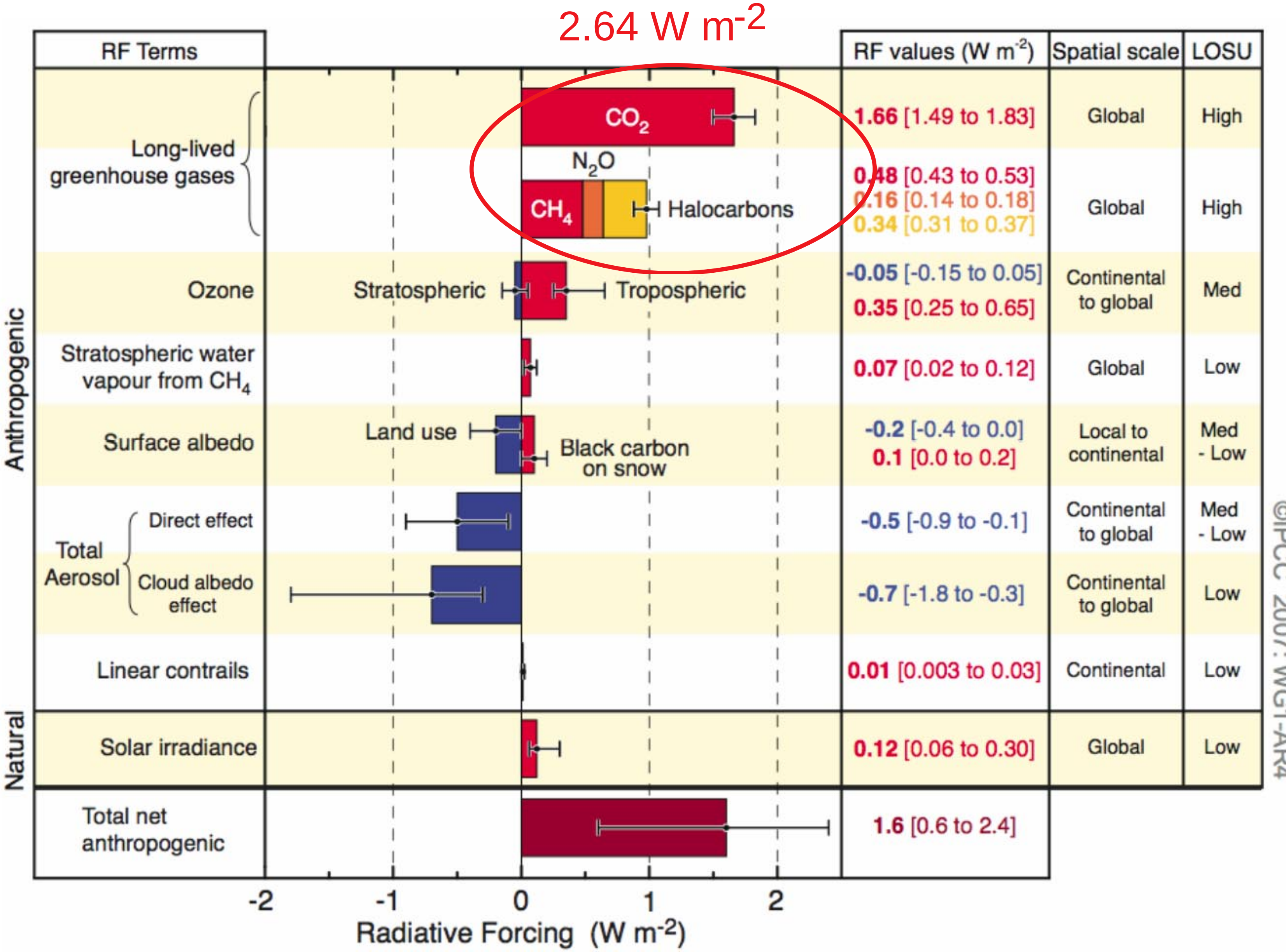

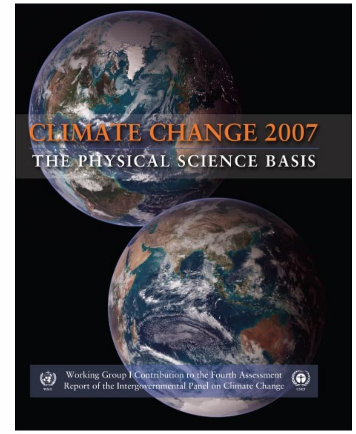

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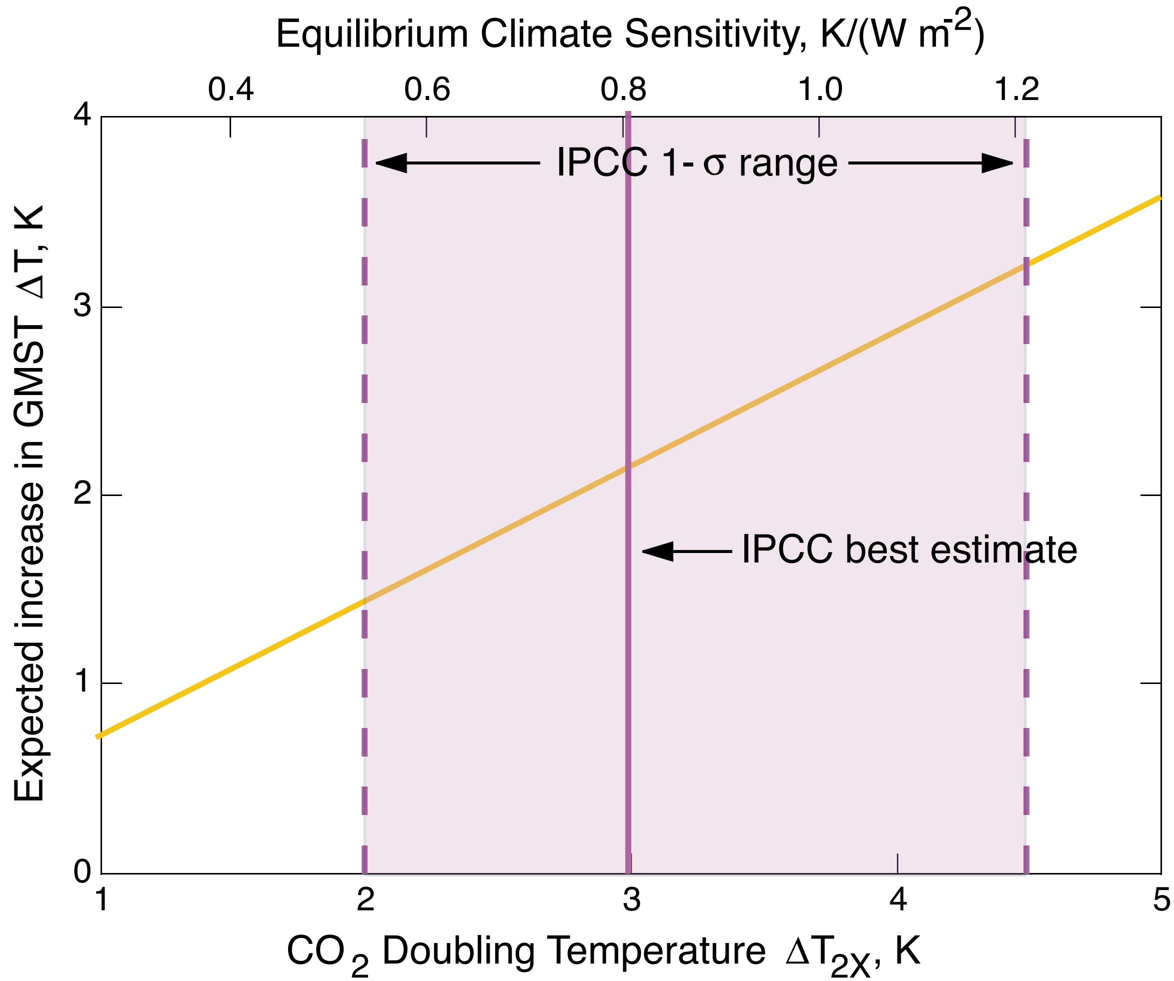
IMPLICATIONS OF PRESENT GREENHOUSE FORCING

Expected equilibrium increase in global mean surface temperature as function of climate sensitivity for present GHG forcing = 2.64 W m^{-2}



IPCC 2007 estimate of climate sensitivity, 3 K (range 2.0 – 4.5 K, 1-σ) implies global temperature increase from preindustrial of 2.1 K (range 1.4 – 3.2 K).

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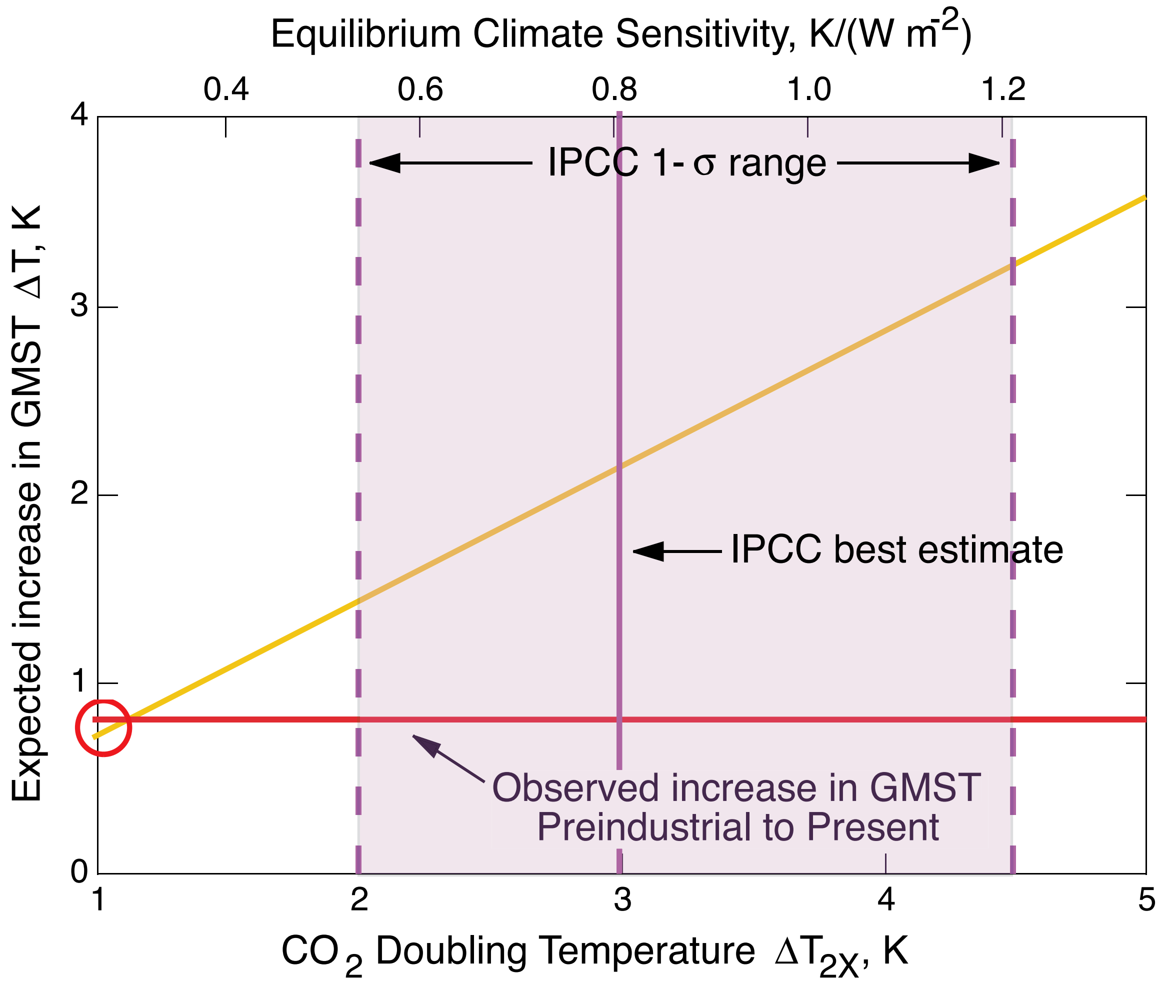

IPCC 2007 estimate of climate sensitivity, 3 K (range 2.0 – 4.5 K, 1-σ) implies global temperature increase from preindustrial of 2.1 K (range 1.4 – 3.2 K). Observed increase in global temperature, 0.8 K, is well less than expected.

WHY IS OBSERVED INCREASE IN GLOBAL TEMPERATURE SO MUCH LESS THAN EXPECTED?

Heating in the pipeline:

Transient sensitivity < Equilibrium sensitivity.

Other forcings not considered:

Aerosols

Estimated climate sensitivity too high:

Sensitivity < IPCC estimates

Forcing-response model does not apply.

Any or all of the above.

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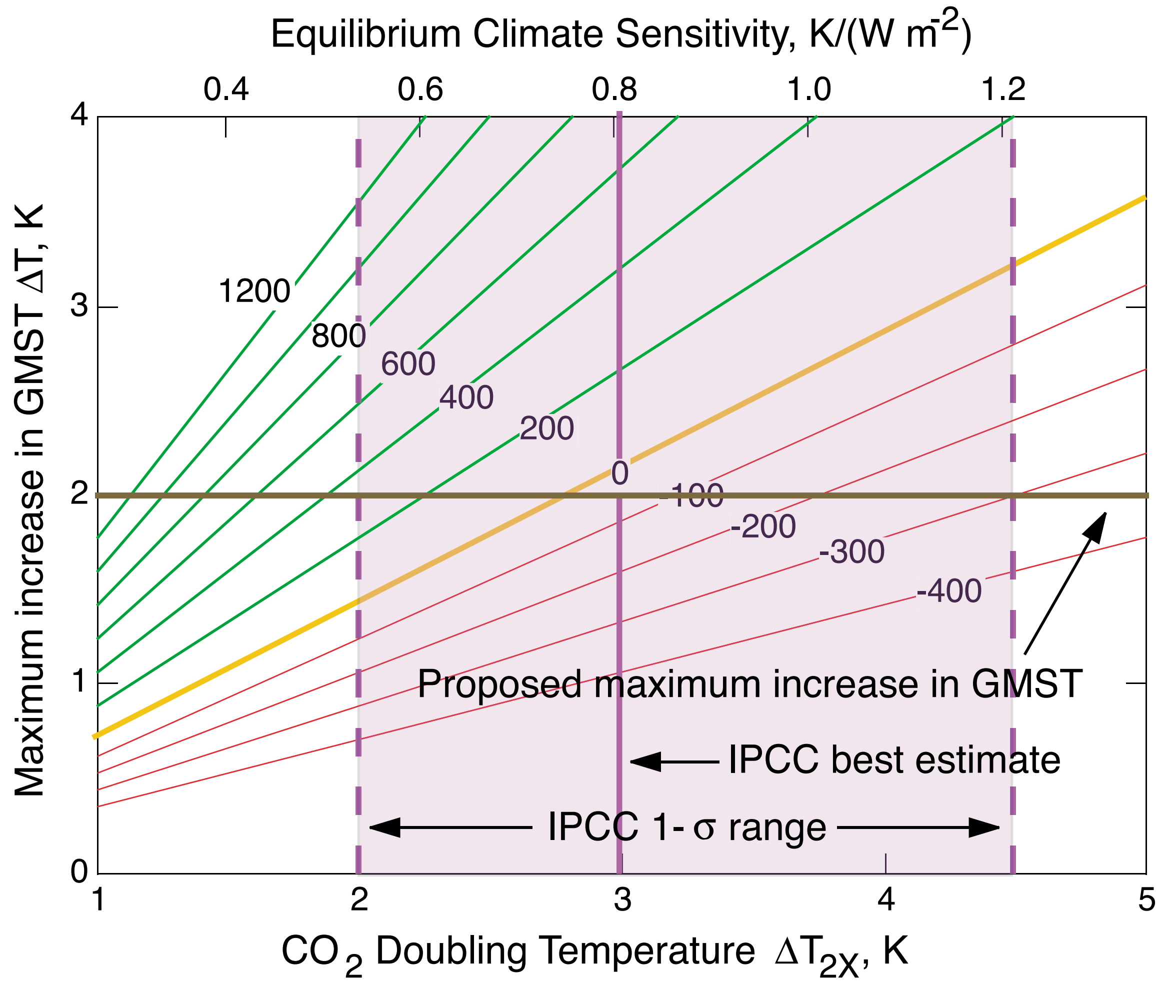
LIMITS ON FUTURE CO_2 EMISSION

Maximum allowable future CO_2 emission (Pg C) for a given allowable increase in global mean surface temperature, as function of climate sensitivity



Commonly accepted maximum increase in global temperature is 2 K.

IPCC 2007 estimate of climate sensitivity is 3 K; range 2.0 – 4.5 K, 1-σ.

Current fossil CO_2 emission rate is ~9 PgC yr^{-1}.

DOE CLIMATE CHANGE RESEARCH PROGRAM STRATEGIC PLAN

DOE Climate Change Research Program: Strategic Plan

December, 2008

***Mission:** Advance the forefront of climate change research to provide the nation with the scientific knowledge it needs about the effects of greenhouse gas emissions on Earth's climate and biosphere to support effective energy and environmental decision making*

The Energy-Climate Issue

Today there is a strong scientific consensus that Earth's climate is changing and that the main causes of global temperature changes in recent decades are anthropogenic. In particular, the consensus is that increasing concentrations of heat-trapping (or "greenhouse") gases in the atmosphere are the chief cause of recent global warming and accelerated sea level rise, and that the carbon dioxide (CO_2) emitted from combustion of fossil fuels is the most important source of growing greenhouse gas concentrations.

The strong link between climate change and greenhouse gas emissions from fossil fuel use makes improving the scientific understanding of ongoing climatic change a priority for the U.S. Department of Energy (DOE).

www.er.doe.gov/ober/CCRD/climate%20strategic%20plan.pdf

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Focus Area 1, Climate Change Process Research:

- The *Atmospheric Radiation Measurement Climate Research Facility* (ACRF). ACRF is a multi-platform national scientific user facility, with platforms and instruments at fixed and varying locations around the globe for obtaining continuous field measurements of climate data to promote the advancement of atmospheric process understanding and climate models through precise observations of atmospheric phenomena.
- The *Atmospheric Radiation Measurement* (ARM) science program. The ARM science program uses data collected by the ACRF and other sources to understand interactions among water vapor, clouds, and radiation transport in order to improve the representation of these processes in climate models.
- The *Atmospheric Science Program* (ASP). The ASP employs laboratory and field studies to develop a comprehensive understanding, and model representation, of the role of aerosols in climate change, including both direct and indirect effects of aerosols on radiation transport in the atmosphere.
- The *Terrestrial Carbon Processes* (TCP) program. TCP uses both field experiments and mechanistic modeling to provide the scientific underpinnings for quantitatively projecting carbon cycle feedbacks to climate change.

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Focus Area 1: Climate Change Process Research
Resolving the most critical uncertainties underlying projections of climate change

Current Situation

Projections of future climate change—which are the basis of national and international policies concerning greenhouse gas emission reductions—are limited by uncertainties in the representation of key physical, chemical, and biological processes in climate models. The three quantitatively most important uncertainties about climate change projections are (1) feedbacks to global warming from changes in clouds, (2) effects of aerosol emissions on the atmospheric radiation balance, and (3) feedbacks to global warming from changes in the carbon balance of the terrestrial biosphere. Research must focus on these processes, and the understanding to be gained from that research must be quickly and effectively incorporated into climate models.

The three *high-priority science questions* that summarize this critically needed research are:

- *What are the present deficiencies in cloud formulations and cloud feedback representations in climate models, and how can they be eliminated?*
- *What are the climatically relevant chemical and physical properties of aerosols that control their effects on the atmosphere's radiation balance, and how can they be best represented in climate models?*
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Aerosols in the Climate System and Climate Change

Aerosols influence climate by absorbing and scattering solar and terrestrial radiation (*direct* aerosol effect) and by modifying the formation and properties of clouds (*indirect* aerosol effect). The global average net effect of present-day aerosols is understood to be a cooling that offsets a substantial portion of the warming that would otherwise occur as a result of presently elevated atmospheric greenhouse gas concentrations, but the magnitude of this offset is uncertain. Indeed, *uncertainty in aerosol-caused perturbations to Earth's present radiation balance exceeds that of all other climate change forcing mechanisms combined. This uncertainty significantly limits the ability to project future climate change and to make informed decisions about candidate energy production or greenhouse gas mitigation strategies that would affect aerosol emissions or properties.*

The spatial and temporal distribution of aerosols, their chemical composition, and their physical attributes (e.g., their optical properties and their role as cloud condensation nuclei) all affect climate. The challenge for properly accounting for aerosols in climate models is to develop simplified representations of complex mixtures of aerosols that are computationally feasible, yet still capture the effects important to climate change. High-priority research needs are improved experimental studies and theoretical interpretations of major aerosol processes, targeted field measurement campaigns in locations having important aerosol types and processes, and development and testing of aerosol process modules suitable for use in climate models.

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Resources

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The Atmospheric Radiation Measurement (ARM) science program and the Atmospheric Science Program (ASP)

The joint ARM/ASP uses coordinated and complementary approaches to quantify the effects of clouds and aerosols on the atmosphere's radiation balance. The joint program uses atmospheric measurements to explore the science of radiation transport processes, clouds, and aerosols in order to increase the fidelity of process representations (and interactions among processes) in climate models. By doing this, it provides needed inputs to the development of the next-generation of climate models, both in the United States and internationally.

The ARM science program leads the advance in treatments of clouds and radiation transfer processes in climate models. It makes extensive use of the ACRF's continuous ground-based observations through a combination of data analysis, modeling of local and regional physics, and development of parameterizations for climate models. It focuses on (1) accurate formulations for both longwave and shortwave radiation transfer calculations for cloudy atmospheres and (2) determination of how knowledge of the large-scale properties of the atmosphere can be used to explicitly simulate the micro-physical and macro-physical properties of clouds within a column of the atmosphere.

The ASP is the only federal research program with a mission to quantify the effects of aerosols on the atmosphere's radiation balance. It uses laboratory studies of the climate-relevant properties of different aerosols, field campaigns to quantify aerosol properties and atmospheric processes in their real-world setting and to test the accuracy of models of aerosols, and theoretical modeling to develop sub-models of aerosols for use in climate models. It focuses on (1) the effects of aerosols on cloud formation and cloud properties and (2) the role of black carbon and organic aerosols in climate change.

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CHIEF SCIENTIST REVIEW

The new DOE Climate Change Research Program Strategic Plan does an ***excellent job***:

- Stating the connection between climate change and energy policy
- Stating the need for climate change research
- Recognizing the role of aerosols as climate forcing agents
- Recognizing the uncertainty in aerosol forcing
- Recognizing the need for understanding and model representation of aerosol processes and properties pertinent to aerosol forcing
- Recognizing the need for research on aerosol forcing
- Recognizing the suitability of ASP approach: Laboratory studies, Field campaigns and Modeling
- Recognizing the importance of joint activities between ASP and ARM where appropriate.

CHIEF SCIENTIST REVIEW (cont'd)

I ***question the advisability*** of language such as:

> The joint ARM/ASP is the only climate research program that seeks a holistic view of clouds, aerosols, and the atmosphere's radiation balance, including their interactions across a range of spatial and temporal scales.

I ***have concerns*** about the future of ASP as an independent program in CESD from the repeated use of the phrase:

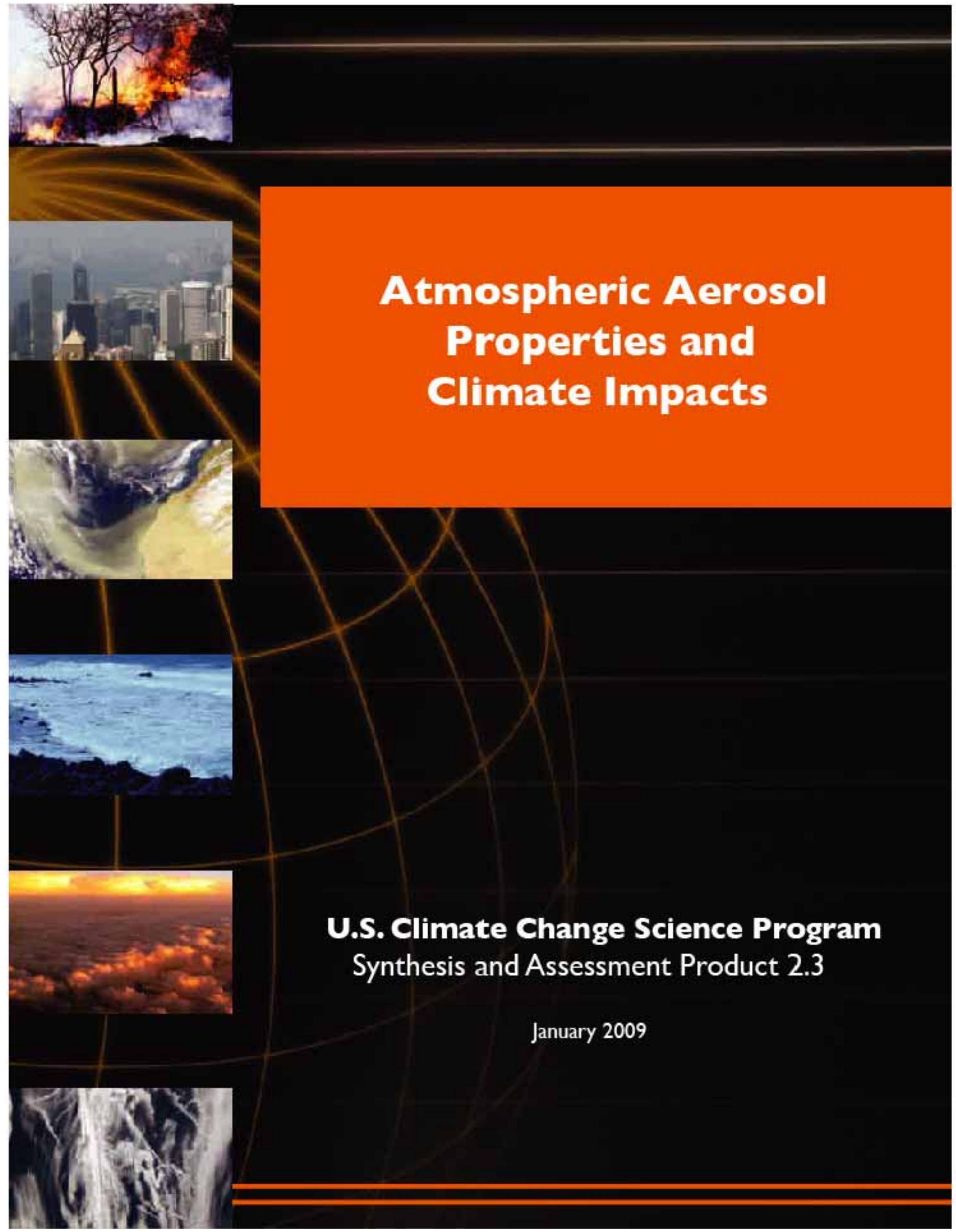
> The joint ARM/ASP
>
> The joint program

CLIMATE CHANGE SCIENCE PROGRAM SYNTHESIS AND ASSESSMENT PRODUCT 2.3: AEROSOLS

CCSP SYNTHESIS AND ASSESSMENT PRODUCT 2.3

US Climate Change Science Program
www.climatescience.gov

The Strategic Plan for the U.S. Climate Change Science Program plan calls for the creation of a series of more than 20 synthesis and assessment reports.



http://www.climatescience.gov/Library/sap/sap2-3/final-report/default.htm

Atmospheric Aerosol Properties and Climate Impacts

Synthesis and Assessment Product 2.3
Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research

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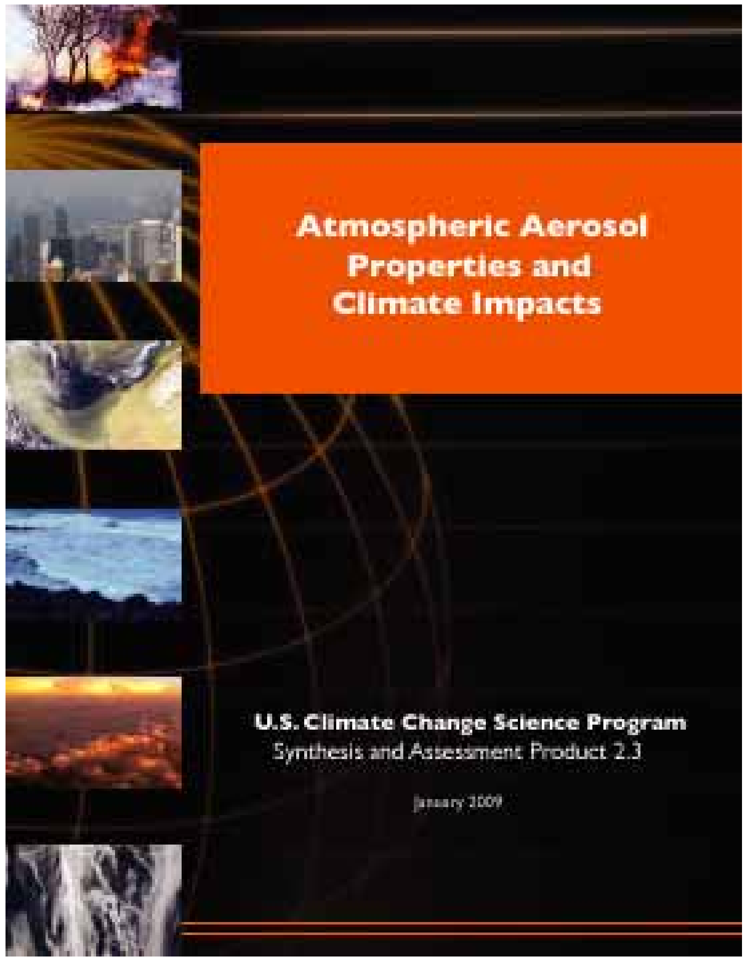
Graham Feingold, NOAA ESRL; Patricia K. Quinn, NOAA PMEL;

Stephen E. Schwartz, DOE BNL; David G. Streets, DOE ANL;

Philip DeCola, Rangasayi Halthore, NASA HQ

IMPORTANT DEFINITION



AEROSOL RADIATIVE FORCING DEFINITION

From CCSP SAP 2.3

Aerosol radiative forcing is the net energy flux (downwelling minus upwelling) ***difference*** between an ***initial*** and a ***perturbed*** aerosol loading state, at a specified level in the atmosphere.

There are a number of ***subtleties*** associated with this definition:

(1) The ***initial state*** against which aerosol forcing is assessed must be specified.

(2) A distinction must be made between

Total aerosol RF – Initial state is complete absence of aerosols; and

Anthropogenic aerosol RF - Initial state is natural (preindustrial) aerosol.

(3) In general, total aerosol RF and anthropogenic aerosol RF include energy associated with both the ***shortwave*** (solar) and the ***longwave*** (primarily planetary thermal infrared) radiative components.

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AEROSOL RADIATIVE FORCING DEFINITION *cont'd*

(5) Aerosol RF can be evaluated at the ***surface***, within the atmosphere, or at ***top-of-atmosphere*** (TOA).

(6) Differences between TOA forcing and surface forcing represent ***heating within the atmosphere***.

Atmospheric heating can affect vertical stability, circulation on many scales, cloud formation, and precipitation.

In this document these additional climate effects are ***not included*** in aerosol RF.

(7) Aerosol direct RF can be evaluated under ***cloud-free conditions*** or ***"all-sky"*** conditions.

Cloud-free direct aerosol forcing is ***more easily and more accurately measured or calculated***.

Cloud-free direct aerosol forcing generally exceeds all-sky forcing because clouds mask the aerosol contribution to the scattered light.

Indirect aerosol RF must be evaluated for all-sky conditions.

In this document ***aerosol RF is assessed for all-sky conditions***.

AEROSOL RADIATIVE FORCING DEFINITION *cont'd*

(8) Aerosol RF can be evaluated ***instantaneously***, or ***daily averaged*** (24-hour), or some other time period.

Measurements generally provide instantaneous values.

Models usually consider aerosol RF as a daily average quantity.

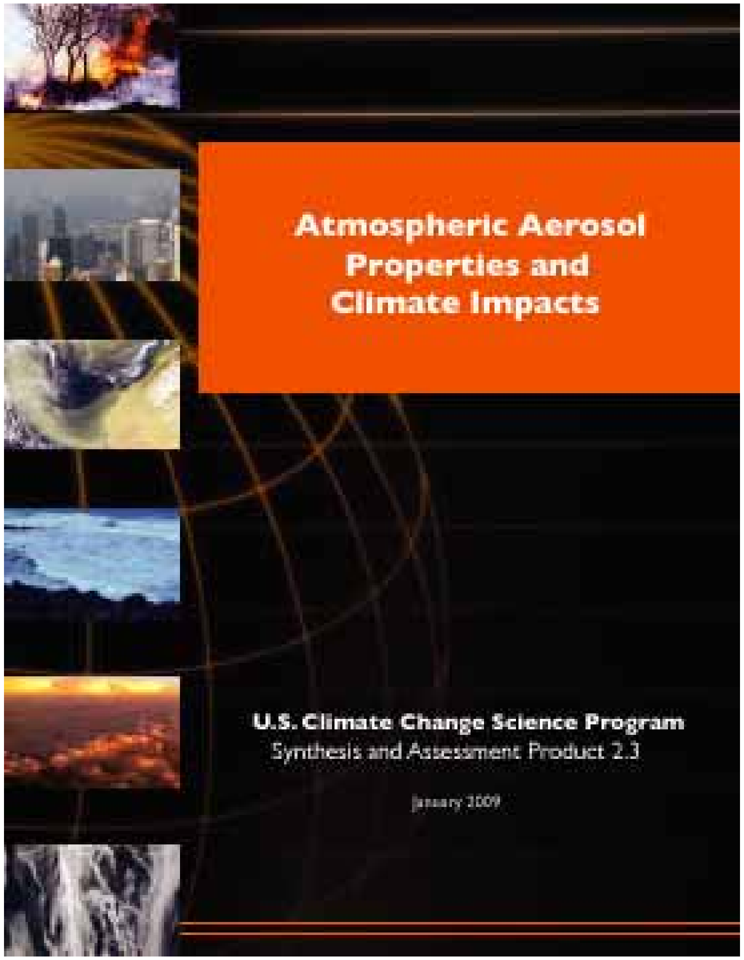
In this document ***daily averaged aerosol RF is reported***.

(9) Another subtlety is the ***distinction between forcing and feedback***.

The concept of aerosol effects on clouds is complicated by the impact clouds have on aerosols.

In this report, ***feedbacks are taken as the consequences of changes in surface or atmospheric temperature***.

SOME KEY FINDINGS



MODELING ATMOSPHERIC AEROSOLS

Simulations of the global aerosol distribution by different models show ***good agreement in their representation of the global mean AOD***, which in general also agrees with satellite-observed values.

However, ***large differences exist*** in model simulations of ***regional*** and ***seasonal*** distributions of AOD, and in the proportion of aerosol mass attributed to ***individual species***.

Each model uses its own estimates of aerosol and precursor emissions and configurations for chemical transformations, microphysical properties, transport, and deposition.

Multi-model experiments indicate that ***differences in the models' atmospheric processes*** play a more important role than differences in emissions in creating the diversity among model results.

MODELING ATMOSPHERIC AEROSOLS (cont'd)

Each model employs its own ***mass extinction efficiency*** based on limited knowledge of optical and physical properties of each aerosol type.

It is possible for the models to produce different distributions of aerosol mass concentrations but agree in their distributions of AOD, and vice-versa.

Progress in improving modeling capabilities requires ***effort on the observational side***, to reduce uncertainties and disagreements among observational data sets.

The way forward will require ***integration of satellite and in-situ measurements into global models***.

TREATMENT OF AEROSOL RADIATIVE FORCING IN CLIMATE MODELS

Despite a wide range of climate sensitivity exhibited by the 20 models in IPCC AR4 simulations, they all yield a global average temperature change very similar to that observed over the past century.

This agreement across models appears to be a consequence of the use of ***very different aerosol forcing values, which compensates for the range of climate sensitivity***.

The direct cooling effect of ***sulfate aerosol*** varied by a ***factor of six*** among the models.

An ***even greater disparity*** was seen in the model treatment of ***black carbon and organic carbon***.

TREATMENT OF AEROSOL RADIATIVE FORCING IN CLIMATE MODELS (cont'd)

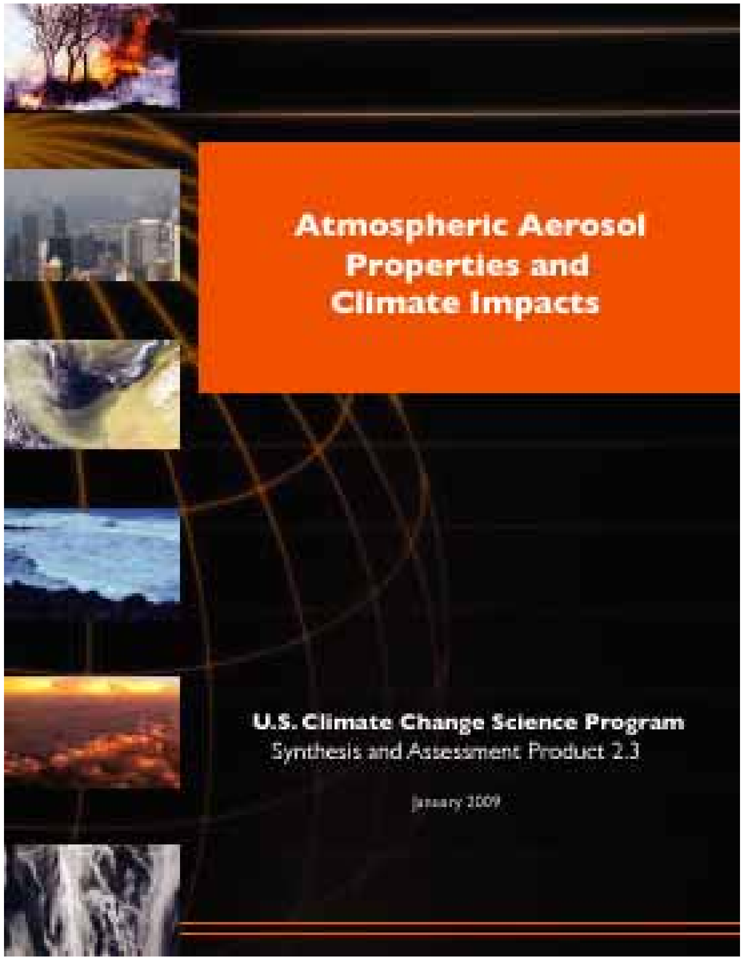
Some models ignored aerosol ***indirect effects*** whereas others included large indirect effects.

For those models that included the ***indirect effect***, the aerosol effect on cloud reflectivity ***varied by up to a factor of nine***.

Therefore, the fact that models have reproduced the global temperature change in the past ***does not imply that their future forecasts are accurate***.

This state of affairs will remain until a firmer estimate of radiative forcing by aerosols, as well as climate sensitivity, is available.

SOME KEY RECOMMENDATIONS



REDUCING UNCERTAINTIES IN AEROSOL RADIATIVE FORCING ESTIMATES

Specific areas where continued, focused effort would likely result in substantial reduction in aerosol forcing uncertainty:

(1) Improving quality and coverage of aerosol ***measurements***,

(2) Achieving ***more effective use of these measurements*** to constrain model simulation/assimilation and to test model parameterizations, and

(3) Producing ***more accurate representation of aerosols and clouds*** in models.

THE WAY FORWARD

Development of new space-based, field and laboratory ***instruments*** will be needed

More realistic simulations of aerosol, cloud and atmospheric processes must be incorporated into models.

Greater synergy among different types of measurements, among different types of models, and especially between measurements and models is critical.

Expansion of aerosol-climate science to encompass ***aerosol effects on cloud processes, precipitation, and weather***.

HIGH PRIORITY OBSERVATIONAL TASKS

- Maintain current and enhance future ***satellite capabilities*** for measuring geographical and vertical distribution of aerosol amount and optical properties, suitable for estimating aerosol forcing over multi-decadal time scales and for evaluating global models.

- Maintain, enhance, and expand the ***surface observation networks*** measuring aerosol optical properties for satellite retrieval validation, model evaluation, and climate change assessments. Augment with systematic measurements of other key parameters with state-of-art techniques.

- Execute a continuing series of ***coordinated field campaigns*** aiming to study the atmospheric processes, to broaden the database of detailed aerosol chemical, physical, and optical/radiative characteristics, to validate remote-sensing retrieval products, and to evaluate chemistry transport models.

HIGH PRIORITY OBSERVATIONAL TASKS (cont'd)

- Initiate and carry out a ***systematic program of simultaneous measurement of aerosol composition and size distribution, cloud microphysical properties, and precipitation variables***.
- ***Fully exploit the existing information in satellite observations*** of AOD and particle type by refining retrieval algorithms, quantifying data quality, extracting greater aerosol information from joint multi-sensor products, and generating uniform, climate-quality data records.
- Measure the formation, evolution, and properties of aerosols under ***controlled laboratory conditions*** to develop mechanistic and quantitative understanding of aerosol formation, chemistry, and dynamics.
- Improve measurement-based techniques for ***distinguishing anthropogenic from natural aerosols*** by combining satellite data analysis with in-situ measurements and modeling methods.

HIGH PRIORITY MODELING TASKS

- Improve the accuracy and capability of model simulation of aerosols (including components and atmospheric processes) and ***aerosol direct radiative forcing***.

- Develop observational strategies to ***constrain and validate the key model parameters***.

- Advance the ability to ***model aerosol-cloud-precipitation interactions*** in climate models, particularly the simulation of clouds, in order to reduce the largest uncertainty in the climate forcing/feedback processes.

HIGH PRIORITY MODELING TASKS (cont'd)

- Incorporate improved representation of aerosol processes in ***coupled aerosol-climate system models***.

- Evaluate the ability of these models to ***simulate present climate and past (twentieth century) climate change***.

- Apply coupled aerosol-climate system models to assess the climate change that would result from alternative scenarios of ***prospective future emissions*** of greenhouse gases and aerosols and aerosol precursors.

EMISSIONS TASKS

- Develop and evaluate ***emission inventories*** of aerosol particles and precursor gases.

- Develop and improve estimates of current emissions, past emissions, and projected future emissions.

ASP CHIEF SCIENTIST REVIEW

It's a really impressive document*!*

Recommended reading for anyone concerned with aerosol influences on climate and climate change.

Certainly recognizes the consequences of uncertainty in aerosol forcing on interpretation of climate change and ability to project future climate change.

Appropriately bold in its call to

> Initiate and carry out a ***systematic program of simultaneous measurement of aerosol composition and size distribution, cloud microphysical properties, and precipitation variables***.

Concerns:

Too incremental in its specification of required future research.

Doesn't come to grips with requirements for emissions research.